FAA-AM-71-17

COMBINED EFFECTS OF ALTITUDE AND HIGH TEMPERATURE ON COMPLEX PERFORMANCE

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16. Abstract

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17. Key Words
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I. Introduction.

A number of the conditions associated with the operation of advanced aircraft have the potential for introducing heat loads on the aircrew (and, in the case of commercial aircraft, on passengers) with possibly deleterious effects on the man's performance capabilities. Thus, an emergency condition involving the loss of both the cooling and cabin pressurization systems would expose the operator to a combined stress situation about which very little is known.

In a previous study conducted at the Civil Aeromedical Institute, we found significant decrements in the performance of aircrew-related tasks during a 30-minute exposure to a temperature of 71.1° C. (an effective temperature of 38.4° C.); both two-dimensional tracking performance and mental arithmetic were adversely affected.[3] Another part of that experiment involved a 30-minute exposure to a temperature of 60° C. (an effective temperature of 35° C.). When the data for the first ten subjects tested at 60° C. were analyzed separately, significant decrements were observed; decrements were not found for the second ten subjects nor for the two samples combined. This finding was interpreted to suggest that the (effective) temperature for performance decrements on a complex task during a 30-minute exposure was at or near 35° C. For the purposes of those experiments and the present experiment, *complex performance* is intended to mean the time-shared performance of several tasks simultaneously.

In each of these previous experiments, testing was carried out at local ground level (1284 ft. MSL). In actuality, a number of the conditions which might result in subjecting aircrew to high temperatures might also be accompanied by an increase in the altitude of the cabin environment. Subsequent to the completion of this study, two reports came to our attention which are relevant to these combined conditions. Allnutt[1] examined the performance of subjects during the final 40 minutes of a 90-minute exposure to 34.4° C. effective temperature combined with a simulated altitude of 10,000 ft. Performance differed significantly (about 10% lower) from a control condition on only one measure, the Cattel IPAT Culture Fair Test of intelligence. In a second experiment[2] the first three subjects exposed to an effective temperature of 34.4° C. combined with a simulated altitude of 15,000 ft. "had to be removed from the environment on medical advice." The criterion of removal, a heart rate of 130 beats per minute, was substantially more conservative than that used in our laboratory. In fact in our previous temperature study, subjects exposed to 71.1° C. (38.4° C. effective temperature) exhibited a mean heart rate of about 135 beats per minute at the end of the 30-minute exposure.

The present study examined the effects of altitude as a variable when added to temperature. A pressure altitude of 14,000 feet was selected to yield a partial pressure of oxygen that would be at or slightly above the threshold for the production of performance decrements as an individually imposed environmental condition. A temperature of 60° C. was selected as a value that was at or just below the threshold for the production of temperature- induced decrements.

II. Methodology.

Subjects. The subjects used in the study were FAA Aeronautical Center male employees who volunteered to participate in response to an item in the Center information bulletin. The selection criteria exercised in recruiting subjects were that they were required to have at least a private pilot's license and a current medical certificate. Nine subjects were used: their ages ranged from 30 to 46.

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Physiological Measures. The following parameters were measured at five-minute intervals during each experimental session using the indicated method: rectal temperature—thermistor probe and Yellow Springs Instrument Co. telethermometer; heart rate—chest electrodes (Telemedic) and a Grass Model 5C polygraph; and weighted average skin temperature—a four-point distribution using copper-constantan thermocouples on the forehead (a weight of 0.10), chest (weight of 0.40), right forearm (weight of 0.14), and right calf (weight of 0.36). All skin temperatures were recorded on a Honeywell Electronik 16 recorder.

Performance Measures. The apparatus used in this investigation was the same as that used in the previously reported study.[1] Since the apparatus was described in detail in the earlier report, it will be mentioned ony briefly here. The subjects performed two primary, active tasks—two-dimensional compensatory tracking and mental arithmetic. They also performed three monitoring tasks—choice reaction to the onset of a red and a green light, simple reaction to the onset of an amber light, and response to the drift of the pointer of either of two meters (drift either up or down from a normally horizontal position). The same combinations of tasks were used as in the previous study—tracking plus the three monitoring tasks; tracking, mental arithmetic, and monitoring; and mental arithmetic and monitoring. These task combinations were performed in 15-minute cycles with five minutes of performance of each of the three combinations in the order listed.

The measures of performance were: tracking—integrated absolute error, integrated error squared and Root Mean Square (RMS) error in each dimension; arithmetic--percentage correct and solution time; red and green lights—reaction time and total time (movement time was derived by subtraction); amber light—response time; and meter monitoring—response time.

Environmental Conditions. All training and testing sessions were conducted in the Civil Aeromedical Institute altitude chamber which is cylindrical in shape; it is 18 feet long, 7 feet 2 inches wide at floor level, and 8 feet 6 inches high. The interior of the chamber was illuminated at a comortable level by fluorescent fixtures. The subject sat on a padded wooden chair with his back toward the door; he was dressed in a short-sleeved, loose shirt, trousers, shoes and socks.

Altitude was controlled in the conventional manner. The temperature was controlled by two methods. The primary system provided a convective input that controlled air temperature directly. However, this system by itself was not capable of achieving the desired rates of temperature increase. Therefore, an auxiliary system of six, 5-kw. radiant heaters was used to bring the temperature up to the specified value in the desired 15-minute period. Once the desired temperature had been reached, the auxiliary heaters were turned on and off as required to maintain the chamber at 60° C. Control of relative humidity was automatic. The convective system maintained a continuous flow of turbulent air at a rate of 50 to 100 feet per minute at the subject position at all temperatures.

The chamber conditions used were as follows:

- Training (Train)—23.9° C. (75° F.); water vapor pressure, 3.1 mm Hg; relative humidity, 14%; altitude, 1284 ft. (MSL) (725.9 mm Hg).
- Temperature (Temp)—60° C. (140° F.): vapor pressure, 17.9 mm Hg; relative humidity, 12%.
- Altitude (Alt)—Temperature and humidity same as for training; altitude, 14,000 ft. MSL (446.6 mm Hg).
- Temperature plus altitude (Temp-Alt)—Temperature and humidity as for the temperature condition; pressure altitude as for the altitude condition.

The environmental profiles are shown in Figure 1. Dry bulb temperature was monitored by means of an air probe located just above and to the right of the subject's head. Subsequent checks showed the black Globe temperature to average about 5° C. below the air temperature.

Procedure. The subjects were given three sessions of training, one on each of three different days. The first session was preceded by a brief physical exam, after which the subject reported to the chamber. During that first session, approximately 15 minutes were devoted to explaining the nature of the experiment, the safety precautions being taken and the nature of each task. Subjects then performed for 15 minutes—five minutes on each of the task combinations; after a short break, the subjects were given a 30-minute training session.

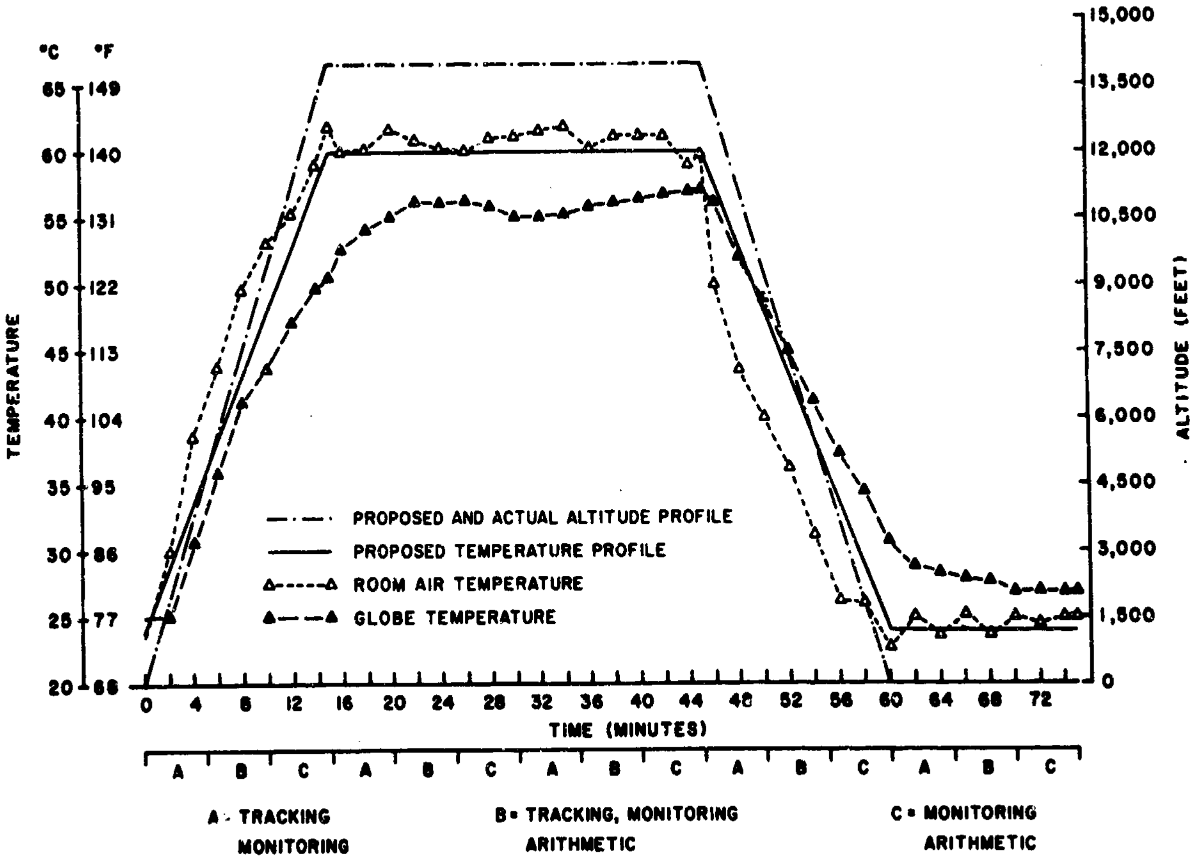

FIGURE 1. Protocol of the experiment. The thermocouple for room air temperature was adjacent to the chamber control sensor and the black globe was at chest level of the subject. Each task combination (A, B, C) was performed for five minutes.

During the second training session, the subjects were given 15 minutes of practice, a short break, and then 75 minutes of practice. In the third training session, the subjects were fitted with all of the physiological recording sensors and were given a 75-minute training session with no breaks. The training was always given at the same time of day (morning or afternoon) that the subject was to be tested.

Subjects reported to the laboratory about 30 minutes before the test session for a given day to be fitted with the physiological recording sensors. They then entered the test chamber, accompanied by the medical monitor, where attachment to the recording apparatus was completed. Subjects were fitted with an absorbent head band to preclude the possibility that perspiration might cause direct interference with vision.

The test profile was the same for each condition. During the first 15 minutes the chamber was shifted from the training condition to the environmental condition for the particular session to be experienced. The chamber was then maintained at that condition for 30 minutes. The environmental condition was then returned to normal over a 15-minute period, and performance testing was continued for 15 minutes for a post-exposure baseline. The order of exposure to conditions was counterbalanced across subjects so that each condition occurred first, second, and third the same number of times (three).

III. Results.

Performance. The data for each of the performance measures were evaluated using a repeated measures analysis of variance model. The variables entered in each analysis were: subjects; environmental condition (Alt, Temp and Temp-Alt); 15- minute interval of the 75-minute session; and 5-minute interval of the 15-minute session (there were two 5-minute intervals per 15-minute interval for arithmetic and tracking measures while the other measures were taken in all three 5-minute intervals).

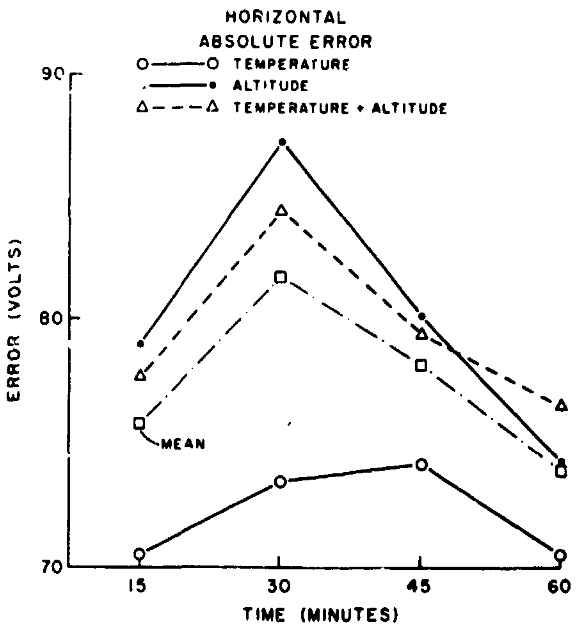

FIGURE 2. Horizontal absolute error in volts (arbitrary scale) on the tracking task. Subperiods of the experimental sessions are plotted for each experimental condition and for the mean of all conditions. Time of initiation of the subperiod is shown on the abscissa.

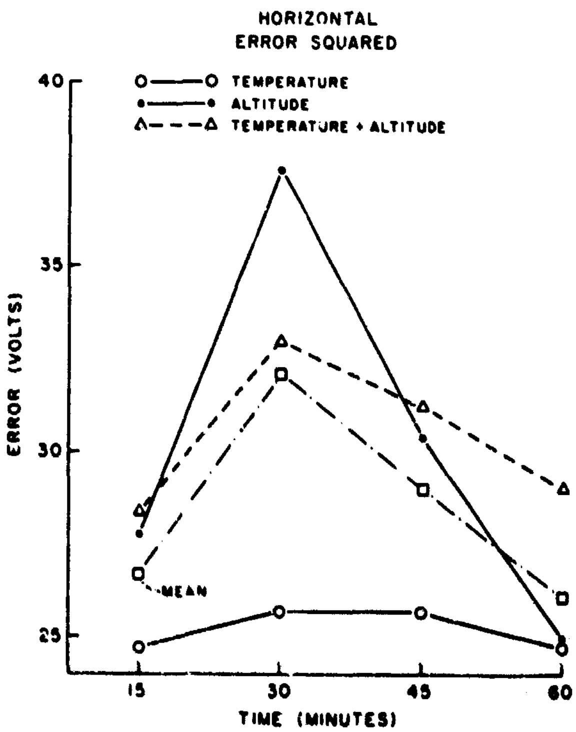

FIGURE 3. Horizontal error squared in volts (arbitrary scale) on the tracking task. Subperiods of the experimental sessions are plotted for each experimental condition and for the mean of all conditions. Time of initiation of the subperiod is shown on the abscissa.

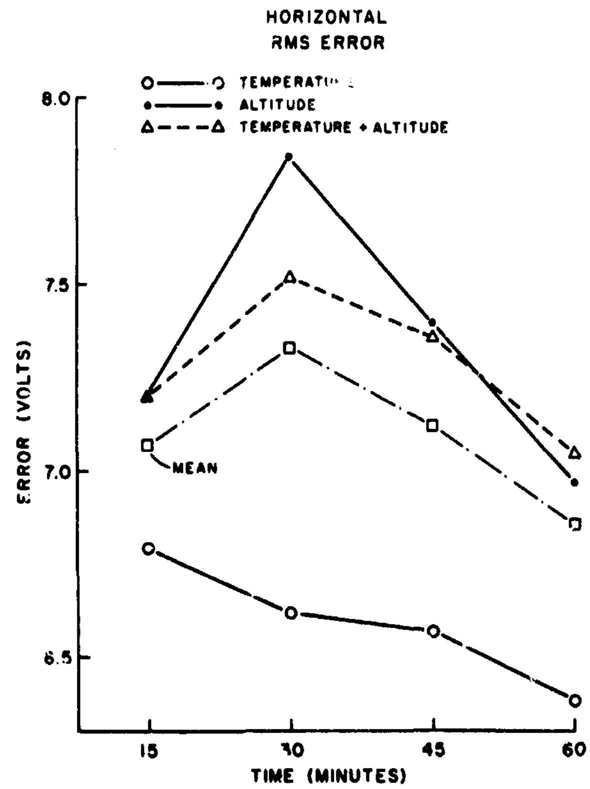

FIGURE 4. Horizontal RMS error in volts (arbitrary scale) on the tracking task. Subperiods of the experimental sessions are plotted for each experimental condition and for the mean of all conditions. Time of initiation of the subperiod is shown on the abscissa.

Significant effects of the environmental conditions were found for four of the six measures of tracking performance, but not for any of the other measures. The effect of environment was significant for the measure of integrated absolute tracking error in the horizontal dimension ($F=4.617$, $P<.05$); integrated absolute error in the vertical dimension ($F=7.917$, $P<.01$); integrated error squared in the vertical dimension ($F=5.808$, $P<.01$); and Root Mean Square error in the vertical dimension ($F=6.465$, $P<.01$). In each case the degrees of freedom for the F-test were 2 and 16. For none of these measures was the interactions of the environmental condition with any of the other variables significant. For all but one of the tracking measures (RMS error, vertical dimension) the effect of 15-minute period (time) was significant; i.e., there was significant variation in tracking performance during the course of the 75-minute test period. (For Root Mean Square error in the vertical

dimension, .10<P<.20.) There were significant differences between 5-minute intervals for all six measures of tracking performance; this corresponds to the effect of the simultaneous performance of arithmetic and tracking as compared to tracking by itself.

The effect of environmental conditions on tracking performance is shown graphically in Figures 2 through 7. In each case, the Alt and Temp-Alt conditions are quite similar and both reflect substantially poorer performance than the Temp condition. This apparent effect was evaluated by the application of non-parametric tests (Wilcoxon T) to the Temp versus the Alt data and the Temp versus Temp-Alt data. (Since this is a non-parametric test, the error squared and the RMS measures would be expected to reveal the same results; hence, only the error squared data were subjected to the Wilcoxon T analysis.) The results of this analysis showed the Temp condition to differ significantly from the Temp-Alt condition for all four measures analyzed—horizontal absolute ($P<.05$), horizontal error squared ($P<.01$), vertical absolute ($P<.01$), and vertical error squared ($P<.01$). For the comparison of the Temp and the Alt conditions, neither measure of horizontal error was significant but both measures of vertical error were significant ($P<.01$ in each case).

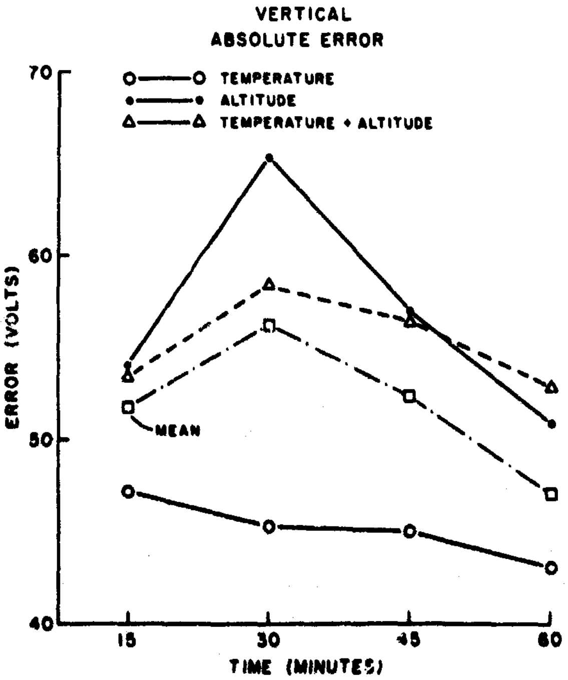

FIGURE 5. Vertical absolute error in volts (arbitrary scale) on the tracking task. Subperiods of the experimental sessions are plotted for each experimental condition and for the mean of all conditions. Time of initiation of the subperiod is shown on the abscissa.

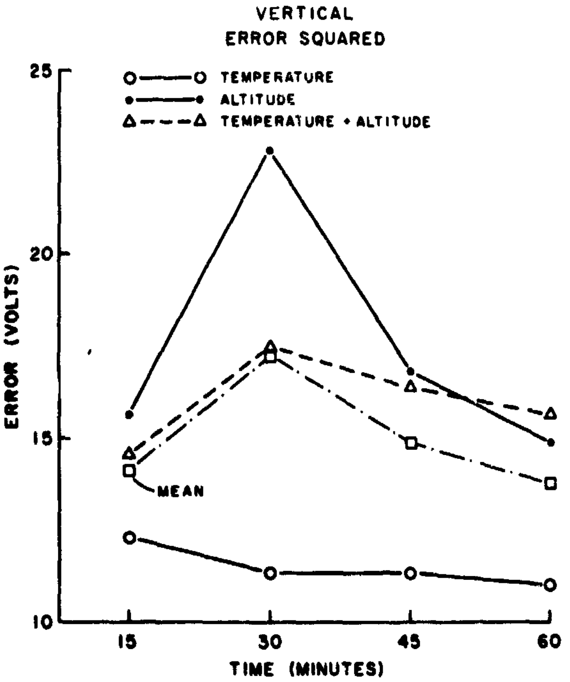

FIGURE 6. Vertical error squared in volts (arbitrary scale) on the tracking task. Subperiods of the experimental sessions are plotted for each experimental condition and for the mean of all conditions. Time of initiation of the subperiod is shown on the abscissa.

As noted in the two preceding paragraphs, the environmental condition was significant for several tracking measures, the 15-minute period was significant for all but one tracking measure, and the two variables did not interact. The effects of the 15-minute period, averaged over the three environmental conditions are also shown (as the squares connected by dashed lines) in Figures 2 through 7. Although there are differences in the shapes of the curves for the individual conditions (especially in the Temp curve as compared to the other two conditions), as was just noted, the interaction of 15-minute period and condition was not significant. This means that, within the limits of the statistical power of the experiment, time has about the same effect irrespective of the environment being considered.

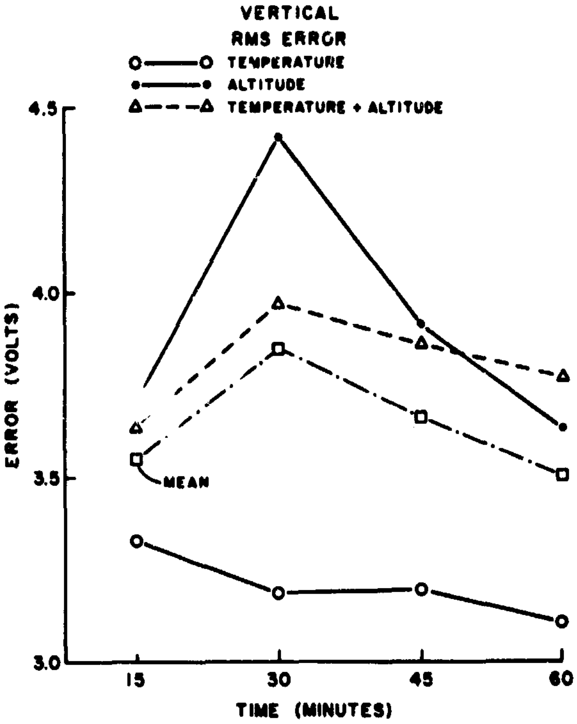

FIGURE 7. Vertical RMS in volts (arbitrary scale) on the tracking task. Subperiods of the experimental sessions are plotted for each experimental condition and for the mean of all conditions. Time of initiation of the subperiod is shown on the abscissa.

Again, Wilcoxon T tests were applied to clarify this question. The performance of the subjects during the two 15-minute periods at the environmental "extreme" was compared with their performance during the 15 minutes of post-exposure baseline performance. A separate analysis was carried out for each environmental condition for each of the two 15-minute periods at the environmental extreme for each of four measures of tracking performance. In the case of the Temp condition, the final 15 minutes (baseline) differed significantly ($P<.05$) from the periods at temperature for only one measure—vertical absolute error; performance was poorer during the first 15 minutes of exposure to the high temperature. In the case of the Alt condition, a significant difference was found for both the horizontal absolute error ($P<.05$) and horizontal error squared ($P<.01$); in each case performance during the second 15-minute period at altitude was poorer than performance during the post-exposure period. In no case was performance during exposure to the Temp-Alt condition significantly poorer than that during the post-exposure period; generally, performance was numerically poorer during the post-exposure period for the Temp-Alt condition than for the Alt condition. Both of these conditions were compared with the Temp condition during this final 15 minutes of the experiment using Wilcoxon T tests (again, the RMS error was not analyzed for either tracking dimension). For no measure did the Alt condition differ significantly from the Temp condition. For three of the four measures (all but horizontal absolute error), the Temp-Alt condition differed significantly from the Temp condition ($P=.05$ or better).

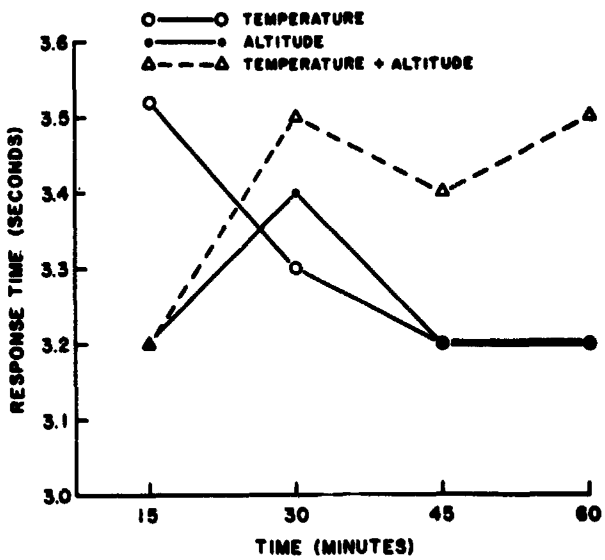

FIGURE 8. Mean response time on the arithmetic task as a function of the experimental subperiod for each experimental session. Abscissa values designate time for the initiation of the subperiod.

The only other finding relevant to performance was a significant interaction ($P<.05$) between environmental condition and 15-minute period in the case of the arithmetic response time measure ($F=2.153$; d.f.$=8.64$). This effect is shown graphically in Figure 8. The apparent effect is that the combination of altitude and temperature has a cumulative influence that does not dissipate upon return to normal room environment conditions; another possible contributor to this interaction is the difference between the Temp condition and the other two conditions during the first 15 minutes at the environmental extreme.

Physiological Responses. The data for heart rate, rectal temperature, and mean skin temperature were analyzed using a repeated measures analysis of variance model; the data of the

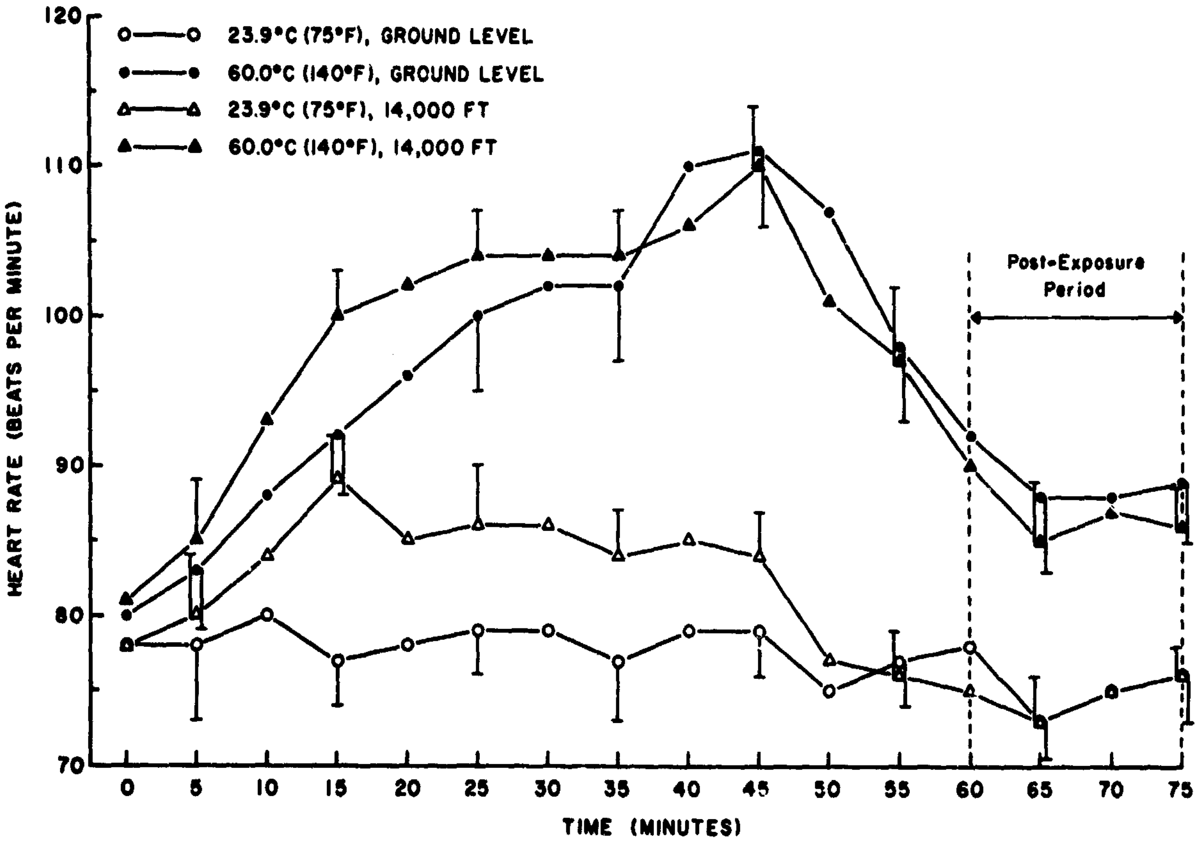

FIGURE 9. Heart rate during exposure to combinations of temperature (23.9° and 60° C.) and altitude (ground level and 14,000 ft.). Values are means with standard error shown at ten minute intervals.

final training session were used as a baseline condition (i.e., normal temperature, ground level atmospheric pressure). The data are plotted graphically in Figures 9, 10A and 10B using the means of the various measures.

Heart rate was significantly increased by the exposure to a temperature of 60° C. ($P<.01$). As seen in Figure 9, for both the Temp and the Temp-Alt conditions, heart rate changed with time ($P<.01$), reaching a maximum rate of approximately 110 beats per minute during the final measurement interval of the period of exposure to the environmental extreme. Heart rate then gradually decreased as the temperature was returned to normal but remained approximately 10 beats per minute above the baseline condition at the end of testing. The Alt condition had a slight but not significant incremental effect on heart rate with an almost immediate return to the baseline rate when the chamber began to descend to ground level.

Rectal temperature was significantly increased by the exposure to 60° C. ($P<.01$) (Figure 10A). For both the Temp and the Temp-Alt conditions, rectal temperature reached a peak 10 to 15 minutes after the beginning of the return of the environment to normal. The peak value in both cases was approximately 0.5° C. higher than at the beginning of the experimental session in question. For the Temp condition, rectal temperature was still at its peak value at the end of the experiment; for the Temp-Alt condition, it showed a slight drop during the final 15 minutes under normal conditions. Altitude did not affect rectal temperature. However, as seen in Figure 10A, there is a suggestion (though not statistically significant) that altitude may have exercised a moderating influence on the effect of ambient temperature on rectal temperature.

Mean skin temperature reflected rather closely the changes in Globe temperature (Figure 10B). The effects of ambient temperature were signifi-

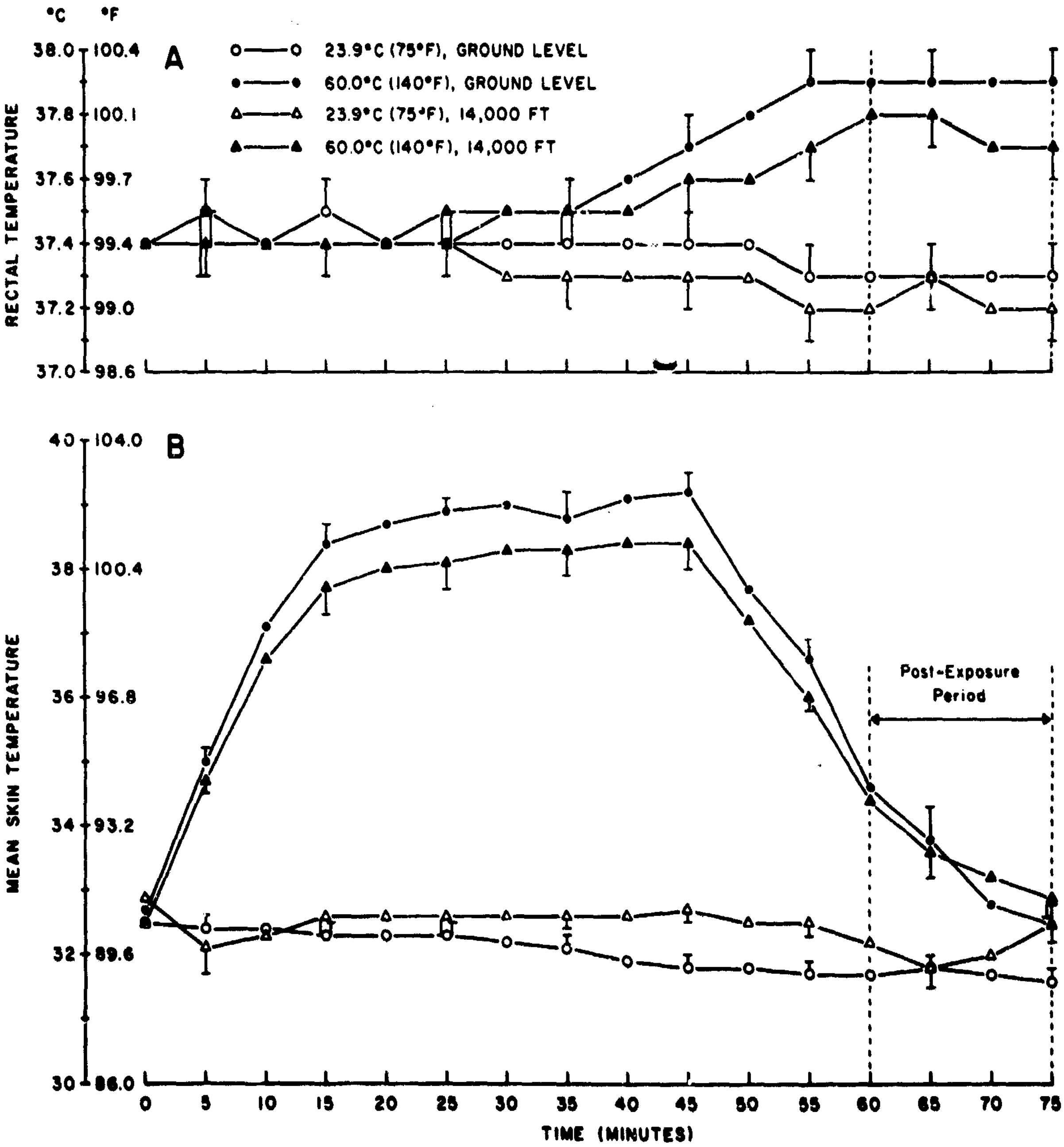

FIGURE 10. Rectal temperature (A) and mean skin temperature (B) during exposure to combinations of temperature (23.9° and 60° C.) and altitude (ground level and 14,000 ft.). Values are means with standard error shown at ten minute intervals.

cant ($P<.01$) for mean skin temperature; the effects of altitude were not significant.

IV. Discussion.

The results rather clearly suggest that, for a 30-minute exposure duration, a pressure altitude of 14,000 feet is a more powerful factor than an ambient temperature of 60° C. in the production of decrements in the performance of tasks of relevance to aircrew activities. Adding the elevated temperature to the altitude condition did little more than "solidify" the apparent effects of altitude alone. For only one measure and one time period was there any evidence of a significant effect of temperature alone on tracking per-

formance, and this finding must be treated as suggestive in that the order of magnitude of the decrement under the Temp condition was much less than that for the Alt condition. Only two pieces of evidence were found for a combined effect of altitude and temperature. One was the observed lack of a significant difference for the Temp-Alt condition when the periods at the environmental extreme were compared with the post-exposure baseline period; the corresponding difference for the Alt condition was significant. The other evidence of a combined effect of the two conditions was the fact that the Temp-Alt condition differed significantly from the Temp condition during this final measurement period, whereas the Alt condition did not. These two findings together are interpreted to suggest that when subjects are exposed to the two environmental extremes in combination, there is a persistent deficit built up that does not dissipate within the 15-minute interval it took to return the environment to normal plus the 10 minutes during which testing on the tracking task was carried out. The statistical mechanism at work would appear to be that there are rather large individual differences in the reaction to exposure to altitude and the dissipation of those effects. Adding temperature to altitude results in a more uniform response to the condition across subjects.

Several possible factors may have been operating to cause the persistent decrement in performance during the post-exposure period in the case of the Alt-Temp condition, but one is prominent among these. During exposure to this condition, the subject's oxygen requirement is increased (because of increased tissue oxygen requirements related to increased body temperature); at the same time, his blood oxygen saturation has decreased because of the reduced partial pressure of oxygen at 14,000 feet. The increased body temperature persists during the post-exposure period, and, therefore, the tissue requirement for oxygen remains high during this period. Unfortunately, blood oxygen saturation was not measured in this study. Therefore, we can only speculate that the pre-exposure oxygen saturation level was not re-established after returning to ground level and, thus, left the subjects relatively hypoxic during the post-exposure period. This relative hypoxia could have been the cause of the persistent decrement in performance observed under the Alt-Temp condition.

The only measured behavior that suffered from exposure to the two environmental conditions (acting either jointly or for altitude alone) was tracking performance. This task, much more so than the others, requires sustained attention but with a high degree of flexibility if the time-shared performance of tracking and the other tasks is to be maintained without decrements. The amount of training given the subjects was adequate to assure that they had acquired the necessary arithmetical and scanning skills to maintain their performance on the monitoring and arithmetic tasks. However, any decrease in their ability to shift back and forth between arithmetic and monitoring on the one hand, and tracking on the other, would most likely be reflected in decrements in tracking performance. Our rationale for this assertion is as follows: First, the stimulus to which the subject responded in the case of the tracking task was much less compelling than the stimuli to which the subject responded on the other tasks. Second, since tracking involves a continuous succession of display changes (whereas the other tasks involve discrete display elements), tracking would be more likely to suffer from momentary lapses of attention or slowness in the shift of attention; this involves a simple probability inference. And third, tracking is the only task in which the subject himself can exert a direct influence on the momentary difficulty of the task; he may inadvertently introduce error which he then must cancel out. The absence of decrements on the monitoring and arithmetic tasks suggests that the decrements in tracking performance were not the direct result of interference with the neuromuscular system. A more likely explanation is that the two environmental conditions, either directly or through the production of interfering responses, alter a central, attentional process and that the tracking task, for the reasons noted above, is more sensitive to such an alteration.

The measured physiological responses of the subjects were very close to those that would be expected from previous research on the two variables.

V. Summary and Conclusions.

Nine well-trained subjects were tested on a complex performance device designed to assess functions of importance to aircrew activities; the

tasks, which involved tracking, monitoring, and arithmetic, were performed during exposures to 14,000 feet altitude and 60° C. (140° F.) ambient air temperature, both singly and in combination. Several physiological measures were made. Exposure durations were 30 minutes for each condition, preceded by a 15-minute period required to reach the environmental extreme and followed by both (a) a 15-minute period during which the environment was returned to normal, and (b) a 15-minute period under normal conditions. Performance testing was carried on throughout the 75-minute test session. Recordings were made of heart rate, rectal temperature, mean skin temperature, and finger temperature.

The only clear-cut effects of the conditions were the significant differences across environmental conditions on tracking performance. Altitude was clearly a more powerful variable than temperature in this study. This was evidenced by the fact that performance under the temperature-plus-altitude and the altitude-only condition was approximately the same; performance under the temperature-only condition was significantly better than for either of the other two conditions.

Evidence for an effect of temperature acting by itself was only suggestive. There was some evidence that the two environments combined produced a persistent effect on performance that did not dissipate with return to normal conditions. The measured physiological responses were well within expectations from previous research with no evidence of any joint effect of the two environmental conditions.

The following conclusions are drawn from this study:

1. Exposure to an altitude of 14,000 feet for 30 minutes produces decrements in a perceptual motor task related to the manual control of an aircraft. Specifically, two-dimensional compensatory tracking suffers when that task is time shared with monitoring and with arithmetic tasks.

2. Decrements will be no larger but may be more consistent across subjects if the exposure conditions involve both 14,000 feet and 60° C. in combination. Decrements may also be more persistent under this condition.

3. Exposure to 60° C. for 30 minutes is probably at or near the threshold for the production of performance decrements.

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